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SATELLITE LASER RANGING WORK AT THE GODDARD SPACE FLIGHT CENTER

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SATELLITE LASER RANGING WORK AT THE GODDARD SPACE FLIGHT CENTER

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INTRODUCTION

The feasibility of using pulsed lasers to range to aritficial earth satellites was first demonstrated by the Goddard Space Flight Center in 1964 when laser returns from the BEACON Explorer Satellite were observed.[1] Since that time, nearly a dozen retroreflector equipped satellites have been launched and tracked with ever increasing precision. The system accuracy has improved from the several meter level of the first systems to better than 10 cm in regular satellite tracking operations. The ranging data has been used for precise satellite orbit determination,[2] for determining polar motion,[3] earth tidal parameters,[4] for measuring with great precision the distance between laser sites[5] and for calibration of spaceborne radar altimeters.[6] The purpose of this paper is to describe the systems presently being operated by the Goddard Space Flight Center, their range and accuracy capabilities, and planned improvements for future systems. In short, GSFC is currently operating one fixed and two mobile laser ranging systems. They have demonstrated better than 10 cm accuracy both on a carefully surveyed ground range and in regular satellite ranging operations. They are capable of ranging to all currently launched retroreflector equipped satellites with the exception of Timation III. A third mobile system is currently nearing completion which will be accurate to better than 5 cm and will be capable of ranging to distant satellites such as Timation III and the soon to be launched LAGEOS.

SYSTEM DESCRIPTION

Very simply stated, a pulsed laser ranging system determines the range to a target by measuring the time of flight of a short pulse of intense light to the target and back. The time of flight is then multiplied by the velocity of light to give the range to the target. The block diagram of the systems currently in use by the Goddard Space Flight Center is shown in Figure 1. A precision timing system produces a pulse once each second which initiates the firing of the laser transmitter. A small sample of the transmitted energy is detected by a photodiode. The output pulse from the photodiode is used to trigger a fixed threshold discriminator which starts the range time interval unit. Similarly, the return pulse from the target is detected by a photomultiplier tube which also triggers a fixed threshold discriminator stopping the range time interval unit. Because the precise time of starting and stopping the range time interval unit is a function of the amplitude and shape of the leading edge of the transmitted and received pulses, small corrections to the gross range word are made by sampling and recording the exact shape and amplitude of the transmitted and received pulses using the waveform digitizers. Thus the center of the transmitted and received pulses is used as the reference point on the pulse. The beginning of the sweep of the appropriate waveform digitizer is controlled by the same pulse which starts or stops the range time interval unit. The epoch time interval unit is used to record the value of the variable time delay between the occurrence of the 1 pps signal from the time standard and the actual firing of the laser. The computer performs the dual role of calculating the azimuth and elevation signals required to drive the telescope mount and of formatting and recording the ranging data for each range observation. Actual preprocessing or reduction of the data is then performed at a central computing facility at Goddard after the data records have been transmitted (usually by mail) from the remote sites. Each site does have the capability of performing a "quick-look" analysis and editing of the data for rapid transmission by teletype to GSFC, however the accuracy of this "quick-look" data is not of the same quality as the final preprocessed data.

MAJOR SUBSYSTEM DESCRIPTION

1. Laser Subsystem

The laser transmitter is perhaps the most important single element of a pulsed laser ranging system. The Goddard systems use a ruby laser which was designed and manufactured by Korad, a division of Hadron, Inc. The lasers have a pulsewidth at the half maximum points of 4 nanoseconds. They operate at a repetition rate of one pulse per second with an energy of 0.25 joules per pulse. In order to achieve this relatively narrow pulsewidth, the lasers are operated in a Q-switched, cavity dump or pulse transmission mode. See Figure 2. In this mode of operation the laser is electro-optically Q-switched after the lamp is flashed by using a Pockel's cell/polarizer combination arranged so that no energy is coupled out of the cavity. When the energy in the cavity has reached a maximum value, the voltage on the Pockel's cell is removed, and the stored energy is entirely

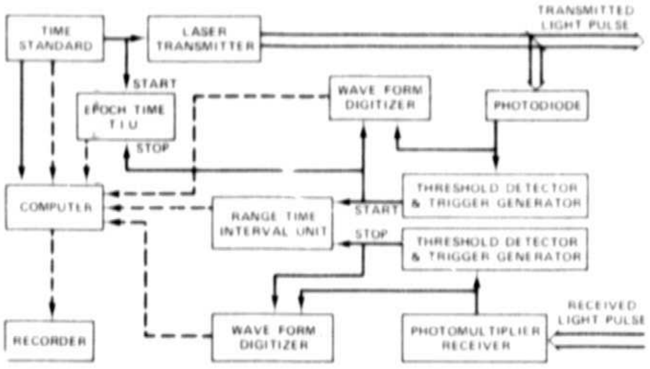

Fig. 1. Laser Ranging System

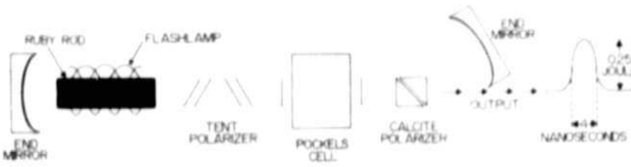

Fig. 2. Cavity Dump Pulsed Ruby Laser

coupled out or "dumped" from the cavity within a four nanosecond period. Thus, the four nanosecond pulse is produced. The advantage of using the cavity dump technique in the ranging application appears to be twofold. The first and most obvious advantage produced by this technique is that the shorter pulse permits higher resolution in determining the time of flight of the pulse to the target and back. Perhaps the more important advantage, however, is that all of the multiple transverse modes of oscillation which occur in a high energy laser of this type are synchronized by the operation of the cavity dump Pockel's cell to leave the system at the same instant of time. The extreme importance of the synchronizing effect arises from the fact that each oscillatory mode has a slightly different radiation pattern from the laser rod. Thus at any point in the far field of the laser transmitter radiation pattern, a unique ensemble of modes exists which is a superposition of the slightly different radiation patterns of each oscillatory mode. In the ranging application, this is no problem if all of the modes started at precisely the same time. However, if the modes do not start at precisely the same time, then the measured time of flight to a target will vary depending on where that target is located in the overall radiation pattern of the laser. The importance of this effect in precision laser ranging systems is perhaps best understood by reviewing the evolution of the various laser systems used by GSFC in achieving the present system accuracy of better than 10 cm. Initially, it was felt that our accuracy goal of 10 cm could be met by using a conventional Q-switched laser with a pulsewidth of nominally 20 nanoseconds in combination with an improved receiver which used the centroid detection technique.[7] However, although the precision of the system improved, the results of satellite tracking tests with two collocated systems were disappointing. We discovered in ranging to a small corner cube on a carefully surveyed ground range that bias errors as large as one meter could be produced by the systems depending upon where the target was located in the transmitter radiation pattern. This problem was solved on an interim basis by installing a commercially available electro/optical shutter produced by Apollo Lasers, Inc. following our 20 nanosecond Q-switched laser. The electro/optical shutter was adjusted to take a slice of the wider laser pulse when it reached a maximum value and it therefore produced a shorter pulse of approximately 5 nanosecond. It also produced the desirable effect of synchronizing the multiple transverse modes to leave the laser/shutter combination at the same instant of time. After the installation of the electro/optical shutter no angle dependent biases were measurable, and the system precision was also improved. Because of the rather low energy output of the narrower pulse and a rather cumbersome operational layout, we have now installed the cavity dump lasers described above in all of our systems.

2. Optical/Mechanical Subsystem

The role of the transmitter portion of the optical/mechanical subsystem is to collimate the output of the laser and to point the collimated beam at the satellite being tracked. The receiving telescope collects the energy reflected from the satellite and focuses it onto the cathode of a photomultiplier tube.

The transmit optical system employs a coelostat type of arrangement for pointing the transmitted beam. This arrangement of two fixed and two movable flat mirrors then permits the laser to be mounted in a fixed position with rigid connections to the laser cooling system and power supplies. Two collimators are used to narrow the beam divergence of the laser from 4 milliradians to the desired 0.2 milliradians. A four power Galilean collimator is fixed in position at the output of the laser. This collimator expands the spot size from 3/8 inch to 1.5 inches lowering the energy density to which the coelostat mirrors are exposed. The last movable mirror of the coelostat is followed by a five power Galilean collimator which moves with the receiver telescope. The use of this collimator after the moving mirrors diminishes by a factor of five the alignment precision required of the coelostat.

The receiver telescope used is approximately twenty inches in diameter and uses a Cassagrain

mirror arrangement with the photomultiplier tube mounted at the prime focus at the rear of the primary mirror. In the ranging application the telescope serves merely as a photon bucket so that diffraction limited optical quality is not necessary.

The mount for the transmit and receive telescopes in the fixed station at GSFC is a special X-Y mount while the mobile systems use extensively modified NIKE-AJAX Az-El mounts. Twenty-two bit inductosyn type encoders are used in conjunction with both types of mounts. After the mounts have been aligned in the conventional way, final calibration is performed by recording the error in position of a series of approximately fifty well distributed stars. These errors are then used in developing an error model for the mounts which is retained in the memory of the digital computer. Using this technique, better than five arc second absolute pointing can be achieved.

3. Receiver Subsystem

The purpose of the receiver subsystem is to detect the light pulses from the laser transmitter and receiver telescope, and to measure precisely the time of flight of the light pulse to the target and back. The main elements of the receiver subsystem are the photodiode for detecting the transmitted pulse, the photomultiplier tube for detecting the much weaker received pulse, two fixed threshold pulse height discriminators, two waveform digitizers and finally a time interval unit. See Figure 1.

There are no special requirements on the photodiode and any of a number of standard units will suffice. The photomultiplier used in the Goddard systems is an Amperex 56TVP. Although this is an old design, it combines a number of characteristics useful in the ranging application. It has high gain, high output current capability, it can be readily range gated to control average background, it has relatively good transit time stability, and it is rugged and low in cost.

The output of both the photodiode and photomultiplier tube is power divided with part of the signal being used to trigger a fixed threshold discriminator. This discriminator then produces a noise-free step-function output which starts or stops the time interval unit and also starts the sweep of the appropriate waveform digitizer. The second half of the output of the photodiode or photomultiplier, after an appropriate delay, is then sampled by the waveform digitizer and recorded permitting an analysis of the exact shape and amplitude of the pulse. This information about the exact shape and amplitude of the pulse will then be used to make small corrections to the gross range information measured by the time interval unit. The time interval unit is a commercially available computing counter (HP Model 5360A) with 0.1 nanosecond resolution. The time base for the time interval unit is supplied externally by the cesium beam frequency standard which is part of the timing subsystem.

4. Computer/Software Subsystem

With one exception the ranging systems use Honeywell H-516 computers. A Raytheon R520 was used in one system due to equipment availability at the time the systems were built. The significant unique features of the R520 are that it has a 24-bit word length and 8 K of memory, otherwise the hardware and software are functionally similar to those of the H-516 systems. This description will be specifically that of the H-516 systems.

Computer Hardware. The computer hardware is indicated in Figure 3. The H-516 has a 16-bit word length, 16 K of core memory and a 0.96 microsecond memory cycle time. It is equipped with high speed arithmetic, realtime clock and priority interrupt options. Software timing is controlled by a one per second interrupt and for lesser time intervals by a realtime clock interrupt based upon a 10 kHz signal from the time standard.

The digital interface multiplexes up to thirty-two 16-bit input words and thirty-two 16-bit output words to the input/output bus. Console displays and controls consist of discrete pushbuttons and lamps, thumbwheel decimal-digit switches as well as a CRT data display and input keyboard. Also input via the digital interface are the time-of-year, the mount pointing angles (encoders), digitized samples of the transmitted and received laser pulses and various measurement and

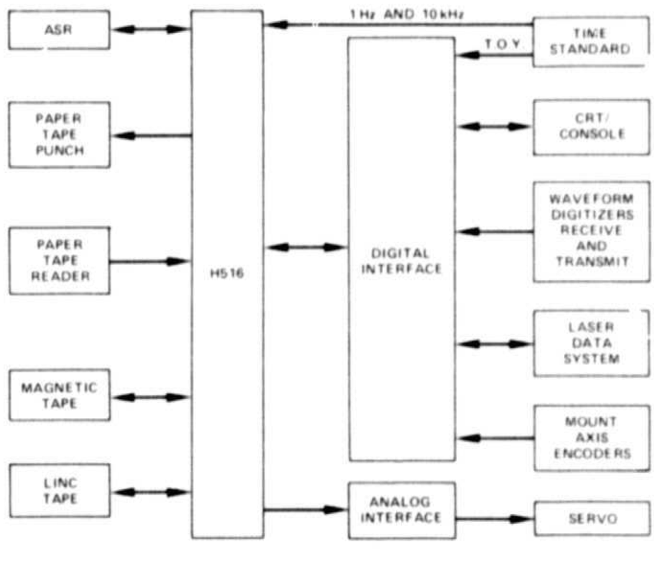

Fig. 3. Computer Hardware System

status data from the laser data system. Predicted range is output to the laser data system. Mount drive signals are output via an analog interface. A teletypewriter is used for non-realtime system initialization, diagnostics and software system generation as are a paper tape punch and paper tape reader. An industry compatible magnetic tape, a file addressable magnetic tape and 8 K of the computer memory are recent hardware additions intended to increase system capability and improve the operation.

Software. The present software system is paper tape based both for application programs and for data recording. It requires 8 K of computer memory. The additional memory and magnetic tape hardware mentioned earlier will, when software modifications are complete, allow the addition of many useful features and will provide a more desirable data media.

The software system consists of a number of stand alone programs each designed to perform a specific function as described below.

a. Telescope Initialization Program (TIP). Orbit prediction data is received from GSFC by teletype in the form of three dimensional, short-arc, polynomial fits to the predicted orbit. TIP reads the teletype paper tapes for the various satellites and merges and sorts the passes chronologically for a week's operation. A daily operating schedule is typed on the teletypewriter giving all passes to be tracked. Also, prepass computations are performed and an array of initialization and prediction data for each pass is written on tape. This tape is read by the realtime tracking program, TOP, and reduces the set-up operations necessary prior to each pass.

b. Telescope Operating Program (TOP). TOP is the realtime system control program. After once reading the initialization data tape TOP generates the telescope pointing command angles (Az-El or X-Y), computes the servo drive signals and the predicted satellite range, interfaces with the operator via the control console and with the hardware system via the analog and digital interfaces and records measurement and status data on tape, all in realtime throughout the tracking operation. Functions having to do with pointing angle computation, operator interface, and data collection and recording are performed at a one-per-second rate. Pointing angle interpolation and mount servo control functions are performed at a 50 millisecond interval synchronized to the one-per-second rate by signals from the time standard.

c. Star Operating Program (SOP). It is usually not cost effective nor practically feasible to build transportable, field operated telescopes and tracking mounts with the maintainable pointing accuracy required in narrow beam laser ranging systems. Systematic errors in the opto-mechanical system can be greatly reduced by a calibration process based upon star observations. SOP is functionally similar to TOP except that it points the telescope to the computer positions of a set of stars scattered throughout the hemisphere and records the pointing error at each star. These data are then processed in non-realtime to determine the coefficients of a mathematical model of the pointing errors. The resulting error model is evaluated in realtime in TOP to transform the shaft angle encoder readings to telescope optical axis angles.

d. A number of supporting programs have been written for hardware testing, software system generation, and for various system development and verification purposes.

5. Timing Subsystem

In order to make optimum use of the highly accurate laser ranging data, it is necessary to time tag the data from the laser stations very accurately. In applications where the data from two or more stations will be merged to determine baselines, polar motion, etc., it is necessary that the clocks at the several stations be synchronized to better than 5 microseconds. Although it is not normally necessary to synchronize this precisely to UTC, the prime time standard maintained in the U.S. by the U.S. Naval Observatory, as a practical matter most of the intercomparison techniques used will accomplish this as well.

The timing system used at the laser ranging system employs a cesium beam frequency standard as the primary frequency reference. Depending upon the geographic location of the station a variety of techniques are used to set clocks initially and to maintain the required synchronization. The systems are equipped with LORAN-C and VLF receivers and we have used portable atomic clocks where necessary to perform this function.

6. Laser Data Preprocessing

After the laser ranging station has completed a satellite pass, the recorded data is sent to the Goddard Space Flight Center for preprocessing. This is the process by which raw laser ranging data is analyzed, edited, reformatted and made available to the community of users. The basic steps in this process include:

a. applying calibration corrections derived from the prepass and postpass calibration over a known path.

b. applying atmospheric corrections.

c. applying corrections determined by an analysis of the waveform digitizer values.

d. editing of the data to discard obviously invalid points.

e. fitting a short arc orbit to the remaining data.

f. discarding points with errors larger than 3 standard deviations and finally,

g. outputting the data in the desired format to users.

Figure 4 is a plot of the data for a typical satellite pass after it has been preprocessed following the steps outlined above.

In addition to the ranging data, angle data is also made available to the users. The angle measurements are simply the corrected outputs of the precision angle encoders for those observations when returns were received from the satellite, therefore their accuracy is only approximately one half of the transmitted beam divergence or 0.1 milliradians.

OPERATIONAL CONSIDERATIONS

1. Present Operational Systems

At the present time GSFC has three operational laser ranging systems:

Systems	Location
Stalas	GSFC
Moblas 1	Bermuda
Moblas 2	Grand Turk Island

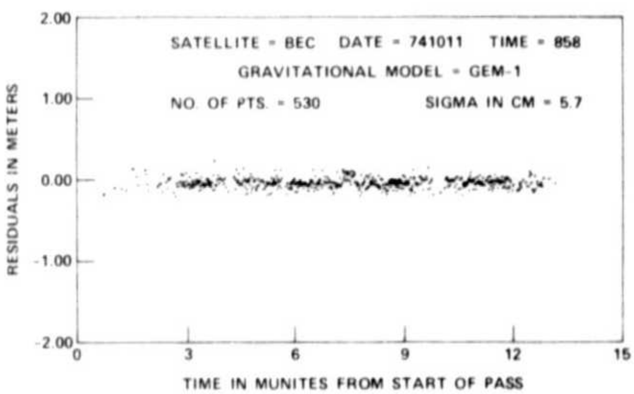

Fig. 4. Stalas Range Residuals Vs. Time

The Moblas 2 laser ranging system is illustrated pictorially in Figure 5.

A third laser ranging system (Moblas 3) is nearing completion and is scheduled to be ready for operation early in 1976. In addition, the Air Force Eastern Test Range is assembling a laser ranging system at the Patrick Air Force Base in Florida. The system, which will be called RAMLAS, will support GEOS-C and other NASA programs starting in August 1975.

2. Mobile Station Layout

A typical mobile laser site requires a fenced area approximately 200 feet square with a 25 foot by 50 foot concrete pad for the laser van. A survey marker isolated from the concrete system pad is required for precisely locating the laser ranging system. Although we also used isolated piers for supporting the laser mount in the past, experience has shown that they are not necessary and we do not plan to use them at future mobile sites.

Typically, five vans are required at a remote mobile laser site. These are:

1. Telescope and laser van
2. Electronics van
3. Radar van
4. Storage and shop van
5. Comfort van

If commercial power is not available, a power generating van is required in addition.

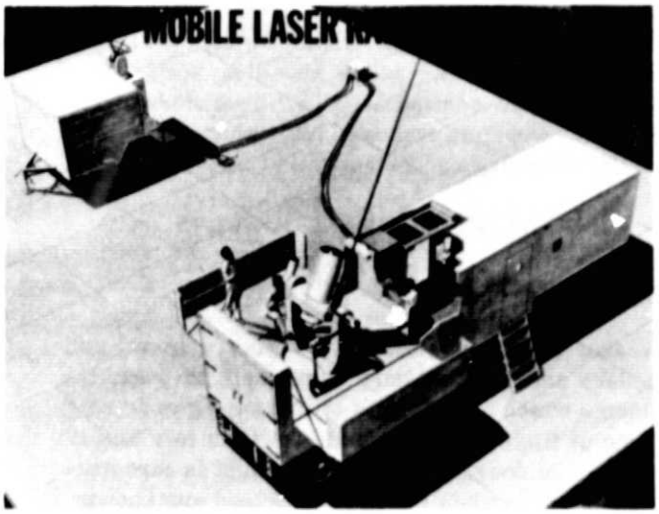

Fig. 5. Mobile Laser Ranging Station

3. Manpower Requirements

There are three operating positions that must be manned in order to take a satellite pass. These are the console operator, the mount operator and the radar operator. A surveillance radar is required to insure that no aircraft in the vicinity of the laser system intercepts the laser beam because of the possibility of eye damage to aircraft occupants.

A typical crew for conducting laser ranging operations on a regular basis is as follows:

1. Crew chief
2. Computer technician
3. Electronic technician
4. Optical/Mechanical technician
5. Radar technician

If more than 40 hours per week of operations are regularly scheduled, additional crew members are needed for efficient operation.

4. Transportability

Moblas 2 and Moblas 3 telescopes are trailer mounted and can be towed over the highway. The Moblas 1 telescope must be transported on a flat bed trailer. The electronics vans can be towed, but the radar and shop vans must be transported on flat bed trailers. The comfort van is normally rented locally and not moved from site to site.

Approximately one week is required to prepare a mobile laser ranging system for transportation to a new site, and about two weeks to set up, align, test and be ready to perform satellite ranging at the new site after arrival. Two weeks should be adequate for a move within the continental U.S. Therefore a minimum of five weeks is required after shut down at one site before ranging can be started at a new site.

PERFORMANCE AND RESULTS

1. System Accuracy

Laser ranging systems are neither primary nor secondary standards of length. Rather, they are instruments which are capable of measuring precisely the time of flight of a short pulse of light to a target and back. Of course, this time of flight is directly related to range when the system delays are known because the velocity of light in free space is known to about 5 parts in 10^8. Thus, the accuracy with which laser ranging systems can be used to measure the distance to a satellite is characterized by a number of factors. First, it is necessary to calibrate the system to a known standard of length to determine the fixed and dynamic (i.e., pulse height dependent) system delays. Second, the "noise" of the instrument or uncertainty in determining the true position of the pulses will limit system performance. Third, the drift or instability of the instrument must not be large compared to the "noise" level. Fourth, since an earth satellite is moving very rapidly, it is essential that the time at which each measurement is made be maintained very accurately. Fifth, since the velocity of light in the atmosphere is different from the free space velocity, atmospheric corrections must be applied. Finally, in a typical spacecraft using an array of corner cubes, the geometric center of the return pulse will be modified by the array.

The error budget for the GSFC systems is given in Table 1. A detailed discussion of each factor in the error budget follows.

Table 1

Laser Ranging Accuracy

	4 ns Laser
Calibration	1.7 cm
Pulse Position Measurement ($10/\sqrt{10}$)	3.3 cm
System Stability	4.0 cm
Clock Synchronization ($5\mu s$)	3.5 cm
Atmospheric Propagation	3.0 cm
S/C Array Geometry ($9/\sqrt{10}$)	2.9 cm
Total RSS	7.7 cm

a. Calibration. The laser ranging system calibration procedure is an end-to-end calibration against a secondary distance standard (Fig. 6). The distance from the laser mount axis to the calibration target is measured with a geodometer. The calibration procedure is to measure the time interval between the transmitted pulse and the received pulse while the signal is attenuated over the entire dynamic range expected on a satellite pass. Approximately 100 points of range data are obtained. Thus, the system is calibrated over a wide range of received pulse heights.

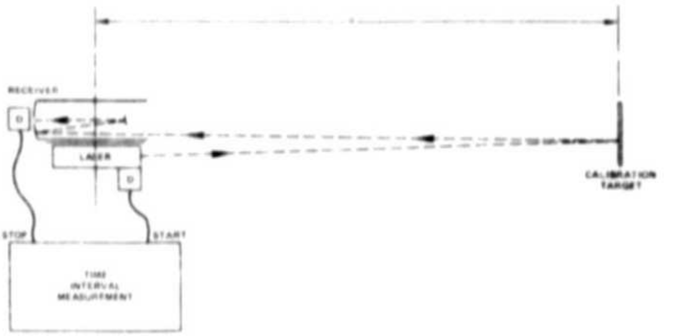

Fig. 6. Laser Ranging System Calibration

This calibration is performed before and after each satellite pass.

The calibration error sources are: the measured distance from the tracker axis to the calibration target, the atmospheric propagation correction, and the precision of the time interval measurement. The accuracy of the measured distance to the calibration target is ±1.5 cm, the accuracy of the atmospheric propagation correction is ±0.6 cm, and the accuracy of the time interval measurement for 100 data points with a measurement RMS of 5 cm is ±0.5 cm. The total calibration error in this case is 1.7 cm taking the root sum square of the various random errors.

b. Pulse Position Measurement. The simplest form of pulse position measurement is a fixed threshold trigger on the leading edge of the pulse. The disadvantage of this method is that the measured position is a function of pulse height and pulse shape.

A better form of pulse position measurement is a constant fraction discriminator on the leading edge of the pulse. This method has the advantage that the measured position is only weakly dependent on pulse height, but is still a function of pulse shape.

The pulse centroid (center of energy) is a better measure of pulse position since it is dependent upon all of the energy in the pulse, rather than upon details of the leading edge. This is the technique currently used in the GSFC systems. In tracking operations we typically achieve single point ranging uncertainties of better than 10 cm. In as much as no unmodeled orbital uncertainties can occur for intervals of less than 10 seconds the single shot uncertainty can be reduced by averaging ten consecutive range readings, thus $10/\sqrt{10} = 3.3$ cm is the uncertainty in determining the range for ten second periods.

c. System Stability. Since the laser systems are calibrated immediately before and after each spacecraft pass, the system must be stable for the duration of the pass if the calibration is to be meaningful. Furthermore, because of the multimode lasers used it is essential to check for angle dependent biases as well as time dependent drifts using small corner cubes which simulate a satellite return more realistically. The system stability of the GSFC systems is shown in Figure 7 for three different targets. The first target is a flat board which is normally used for calibration, and the other two targets are small corner cubes mounted on a pole and a water tank respectively. Figure 8 is a plot of range difference versus transmitter pointing angle. Both these plots confirm

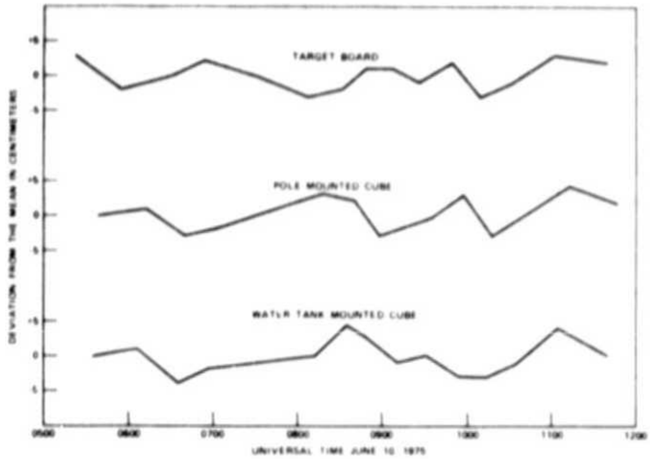

Fig. 7. Stability Test

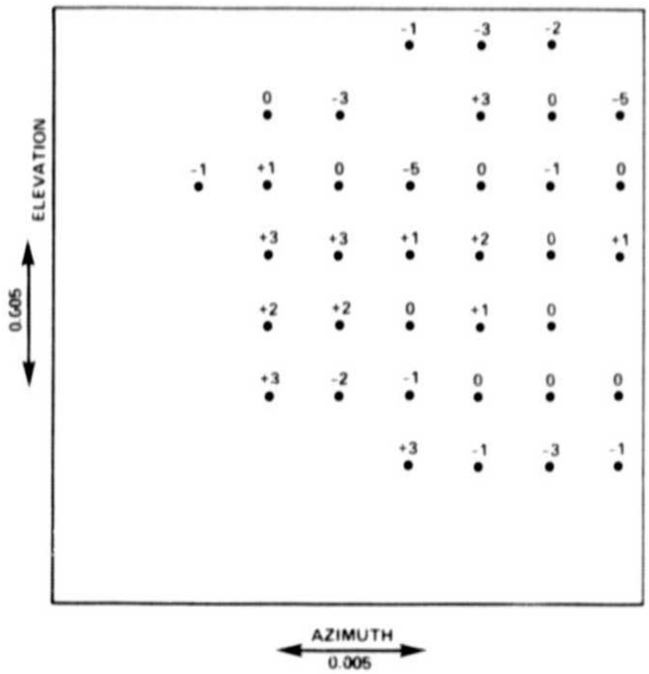

Fig. 8. Range Stability Vs. Pointing Angle

that the overall system stability is within the 4 cm value used in the error budget.

d. Clock Synchronization. The GSFC laser systems are equipped with Cesium standards and LORAN-C receivers. The requirement for time synchronization in the Atlantic calibration area is $\pm 5 \mu s$ between stations. This requirement arises from the fact that a satellite moving in a typical low orbit travels approximately 0.7 cm in one microsecond. Thus, if time is synchronized to within $\pm 5 \mu s$ between sites, the peak error in spacecraft position would be ± 3.5 cm.

e. Atmospheric Propagation Correction. Since the velocity of light is different in the atmosphere than in free space, the ranging data must be corrected for the atmospheric slowing. In general this is done by using an atmospheric model which relates surface pressure, temperature and relative humidity to the total range correction. The model used by the Goddard Space Flight Center was developed by John W. Marini and C. W. Murray, Jr.[8] This model was extensively checked against ray traces using radiosonde atmospheric data and the agreement between the model and the ray traces was better than 0.5 cm even at low elevation angles. Since this intercomparison neglected common mode errors and assumed atmospheric homogeniety, the absolute error is conservatively estimated to be less than 3.0 cm.

System Intercomparison Results. The final and perhaps most complete test of ranging system accuracy is to conduct actual satellite ranging operations with two or more collocated laser ranging systems. Short arc solutions are then made independently using the data from each ranging system. Biases between these two independently determined arcs are then computed. Figure 9 is a plot of the results of a series of intercomparisons of two collocated systems for three different system configurations. Each point on this plot is the result of a separate satellite track by two systems and the error bars represent the uncertainty in determining the bias for each short arc. In general, this uncertainty in determining the bias is dominated by the noise in the data from the individual ranging systems. The first series of 11 tracks were performed in 1971 using the first operational laser systems developed by GSFC.[9,10] These systems used leading edge detection with pulse height correction and the single point uncertainty in the data was typically 50 cm. The second series of 7 tracks were performed in the Fall of 1973 using systems which employed the centroid detection scheme described earlier but using the same lasers (i.e., 20 nanosecond, multimode Q-switched) as the earlier systems. Here, the precision was improved by the

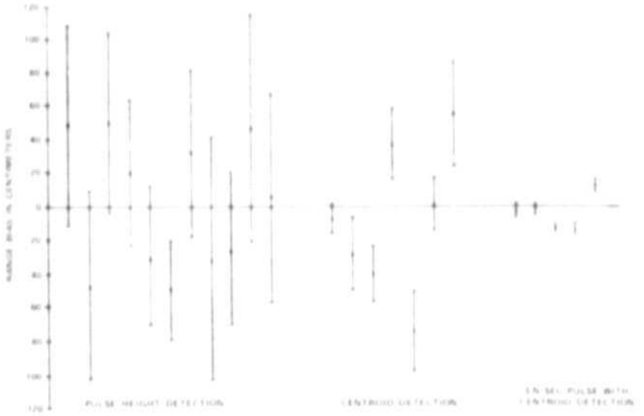

Fig. 9. Laser Ranging Two Station Intercomparison Results

new receiver technique, however, the system biases were approximately the same as the earlier systems. The final series of five tracks were made in late Spring of 1974 using the Moblas 1 and 2 systems with the same Q-switched laser, however, it was now followed by an electro-optical shutter. Here, both the improved precision and reduction in system bias is obvious.

2. System Range Capability

In addition to the accuracy capability of a system, an extremely important characteristic of a laser ranging system is its maximum range. Although it is possible to design systems to operate satisfactorily with less than a single photoelectron average return per shot as in the lunar ranging systems,[11,12] the Goddard systems are not designed to operate in this way. Rather, the centroid detection technique is designed to exploit the higher signal levels available in ranging to targets much closer to the earth. Typically, the threshold is set at a signal level of five photoelectrons per shot to achieve the system accuracy described above. The average number of photoelectrons to be expected for each laser shot can be computed from the well known basic radar equation

$$N = \frac{1}{2\pi} \eta \frac{E_T D_R^2 E_{ff}}{\theta_T^2 h\nu} \cdot \frac{\sigma \alpha_T}{R^4}$$

where:

η = Photomultiplier Tube Quantum Efficiency

E_T = Laser Energy

D_R = Diameter of the Receiving Telescope

E_{ff} = Overall System Efficiency

θ_T = Divergence to 1/e point of the transmitted beam

h = Planks constant

ν = Frequency of the laser radiation

σ = Radar cross section of the target

α_T = Two-way atmospheric transmission

R = Range to the target

The values of the fixed parameters for the GSFC systems are summarized in Table 2.

Table 2

Parameter	Value
η	2%
E_T	0.25 J
D_R	0.51 M
E_{ff}	0.15
θ_T	0.2 milliradians
ν	4.321×10^{14} Hz ($\lambda = 0.6943\,\mu$m)

Peter O. Minott of the Goddard Space Flight Center has calculated and in most cases measured, the cross section of a variety of retroreflector equipped satellites currently in orbit.[13] In the interest of completeness, we have included a summary of his results for the various satellites and the Lunar arrays in Table 3.

The right hand column of Table 3 is a tabulation of the radar cross section for each of the satellites divided by R^4 and is thus an indicator of relative ranging difficulty.

In summary, the present GSFC systems are quite adequate for conducting regular ranging operations to any of the lower satellites including STARLET which is the most difficult of that group. However, improvements will be needed in system capability to reliably range to LAGEOS or Timation.

3. Operational Summary

Upon the completion and testing of the Moblas 1 and Moblas 2 Laser Ranging Systems at the Goddard Optical Research Facility (GORF), they were moved to California for the San Andreas Fault Experiment (SAFE). Moblas 1 was operated at Quincy and Moblas 2 at Otay Mountain near San Diego.

During the period from August 27, 1974 to December 14, 1974 these two systems made range measurements to three retroreflector equipped satellites; GEOS-A, GEOS-B, and BE-C. During this

Table 3

Satellite	Orbital Altitude $M \times 10^6$	Cross Section $M^2 \times 10^6$	Cross Section/(Slant Range)^4 Zenith $M^2 \times 10^{-18}$	45° $M^2 \times 10^{-18}$
1. BE-B	1.13	4.60	2.92	0.918
2. BE-C	1.00	4.60	4.60	1.47
3. GEOS I (A)	1.95	57.2-0	3.96	0.026
4. GEOS II (B)	1.53	100-0	18.2	0.127
5. GEOS III (C)	0.93	3-30	4.01	10
6. LAGEOS	5.90	10.8	0.00891	0.00473
7. Lunar Arrays	360	400	2.38×10^{-8}	2.33×10^{-8}
8. STARLET	0.92	0.55	0.767	0.240
9. Timation III	14.0	103	0.00268	0.00183

operational period, the mobile systems employed the laser electro-optical shutter configuration discussed earlier.

The stationary laser ranging system, Stalas, at GORF also participated in the SAFE program from October 7, 1974 to December 14, 1974 using the cavity dump laser system.

A summary of the performance of the three systems during the 1974 SAFE operation is as follows:

System	Total No. of Passes	Ave. Cal. Range Residual	Ave. Pass Range Residual	Ave. No. Hits Per Pass
Moblas 1	60	4.7 cm	11.6 cm	77
Moblas 2	141	6.1 cm	10.2 cm	159
Stalas	114	5.5 cm	6.7 cm	229

On several occasions during the 1974 SAFE operations, simultaneous ranging to the BE-C satellite by Moblas 2 in San Diego, Cal. and Stalas at Greenbelt, Md. was accomplished. This permitted an accurate determination of the baseline distance between the two sites.

After completing the 1974 SAFE measurements, the two mobile laser ranging systems were moved to the Atlantic Ocean area to support GEOS-C. Moblas 2 was moved first to Wallops Island, Virginia for a short collocation experiment with the Wallops Island laser ranging system and then to Grand Turk Island. Moblas 1 was moved to Bermuda. The Stalas system has also supported GEOS-C. Korad cavity dump laser systems were installed in Moblas 1 and 2 at the time of the move, replacing the laser/electro-optical shutter configuration.

GEOS-C was launched April 9, 1975 and laser ranging started on this satellite April 19, 1975. Five retroreflector equipped satellites have been tracked by the three laser ranging systems since that time with the highest priority given to GEOS-C. A summary of the laser ranging on these satellites from April 9, through June 25, 1975 is as follows:

Satellite	Moblas 1	Moblas 2	Stalas	Total
GEOS-C	11 passes	60 passes	68 passes	139
STARLET	1	16	32	49
BE-C	9	21	38	68
GEOS-A	3	20	24	47
GEOS-B	7	13	7	27
Totals	31	130	169	330

Preprocessed data on these passes is not available at this time, so the range residuals cannot be listed. Since Moblas 1 and 2 are now equipped with cavity dump lasers, it is expected that the range residuals for these two systems will be improved by nearly a factor of two.

FUTURE IMPROVEMENTS

The thrust of the continuing ground laser ranging technology development at GSFC is twofold: (1) to continue the development of technology which will improve both system accuracy and range capability and (2) to develop the technology of cost effective systems which may not represent the state-of-the-art in terms of accuracy but which meet the requirements of a broader class of users for reliable relatively low cost systems. In addition we are developing the technology necessary for performing laser ranging from spacecraft to ground and to other spacecraft for a host of future applications.

The most pressing requirement for immediate system improvements will come with the availability of NASA's LAGEOS satellite. This satellite will be a perfect sphere, 0.60 meters in diameter and equipped with 426 retroreflectors. It will be launched into a very stable circular orbit with an altitude of 5900 kilometers. The excellent geometry and high orbit of this satellite will require more accurate ground systems to take full advantage of potential applications and will require an improvement of approximately a factor of ten over present systems in range capability. The Moblas 3 system presently nearing completion will have an overall system accuracy of better than 5 cm and will incorporate the necessary improvement in range capability. The most important single change will involve the use of a frequency doubled Nd:YAG laser in place of the ruby lasers now being used. We are currently evaluating two candidate systems for the new laser transmitter. The first is an 0.2 nanosecond pulsewidth laser producing 0.25 J of energy at 0.53μ meters wavelength being built for NASA by GTE/Sylvania. The second candidate will be a 5 nanosecond pulsewidth laser not yet under contract. To realize the optimum potential of either of these lasers various receiver subsystem improvements will also be incorporated. Moblas 3 will then serve as the technical forerunner of a new series of laser ranging systems whose procurement is currently being contemplated by NASA for future network applications.

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